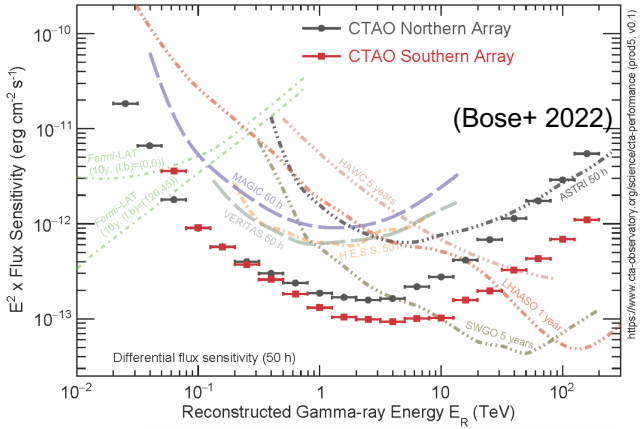
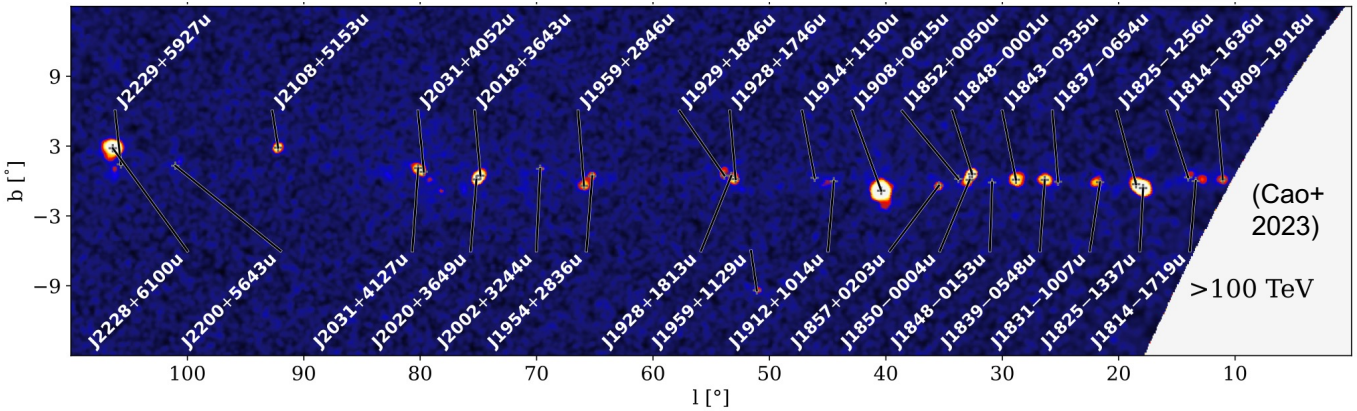
# *VERITAS observation of the unidentified LHAASO sources*

**Jooyun Woo (Columbia University)**
on behalf of the VERITAS collaboration
09/12/2023 TeVPA @ Napoli, Italy

# *LHAASO detected 43 ultra-high-energy (> 100 TeV) sources, the evidence of > 1 PeV CR acceleration.*

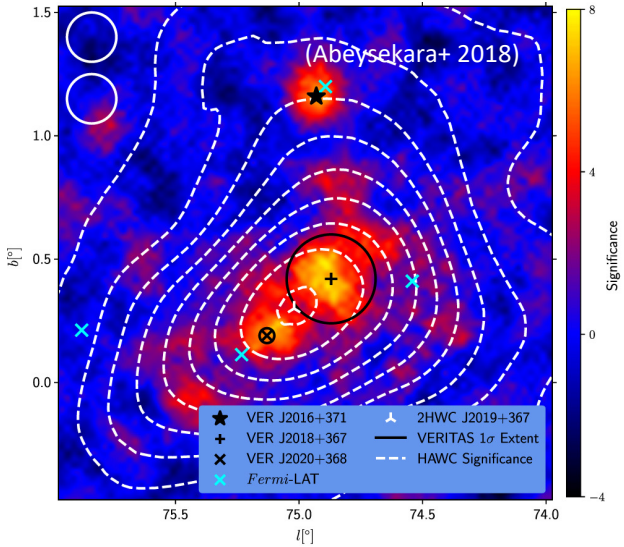
- **LHAASO** joins HAWC in finding Galactic PeVatrons!
  - Unprecedented sensitivity up to **> 1 PeV**
  - Broadband coverage (KM2A (UHE) + **WCDA (VHE)**)
  - **PSF 0.5° @ 20 TeV**, 0.2 ° @ 100 TeV
  - Early release (2021) + first source catalog (2023) = **43 UHE sources (15 new)**

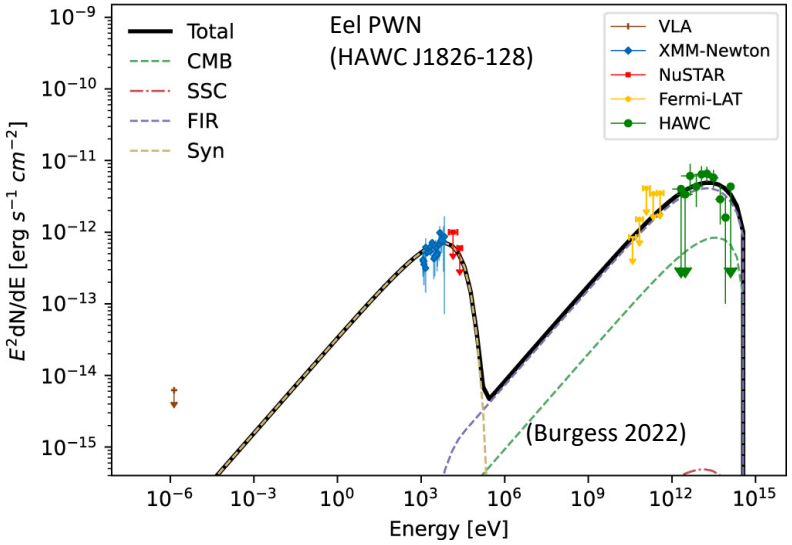


# *IACT follow-up observation of the new UHE LHAASO sources is crucial in identifying Galactic PeVatrons.*

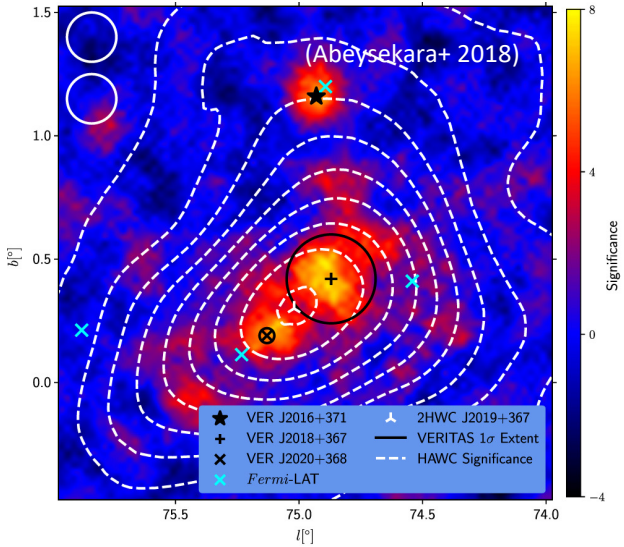
- **IACT (PSF < 0.1° @ 1 TeV)** follow-up is crucial in
  - **Resolving the source confusion**
  - **Providing gamma ray spectrum at / before the peak (complementary to WCDA)**
- \+ **X-ray (NuSTAR, XMM),** GeV (Fermi-LAT) observation = **PeVatron identification!**

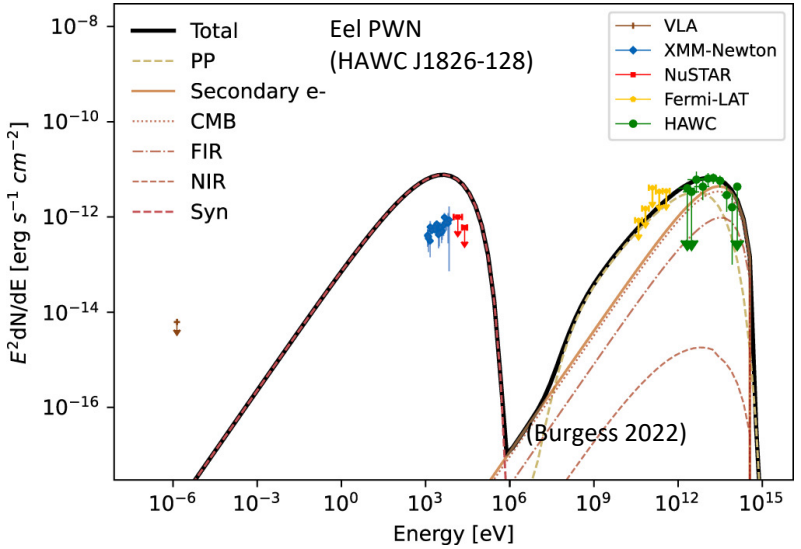


# *IACT follow-up observation of the new UHE LHAASO sources is crucial in identifying Galactic PeVatrons.*

- **IACT (PSF < 0.1° @ 1 TeV)** follow-up is crucial in
  - **Resolving the source confusion**
  - **Providing gamma ray spectrum at / before the peak (complementary to WCDA)**
- \+ **X-ray (NuSTAR, XMM),** GeV (Fermi-LAT) observation = **PeVatron identification!**



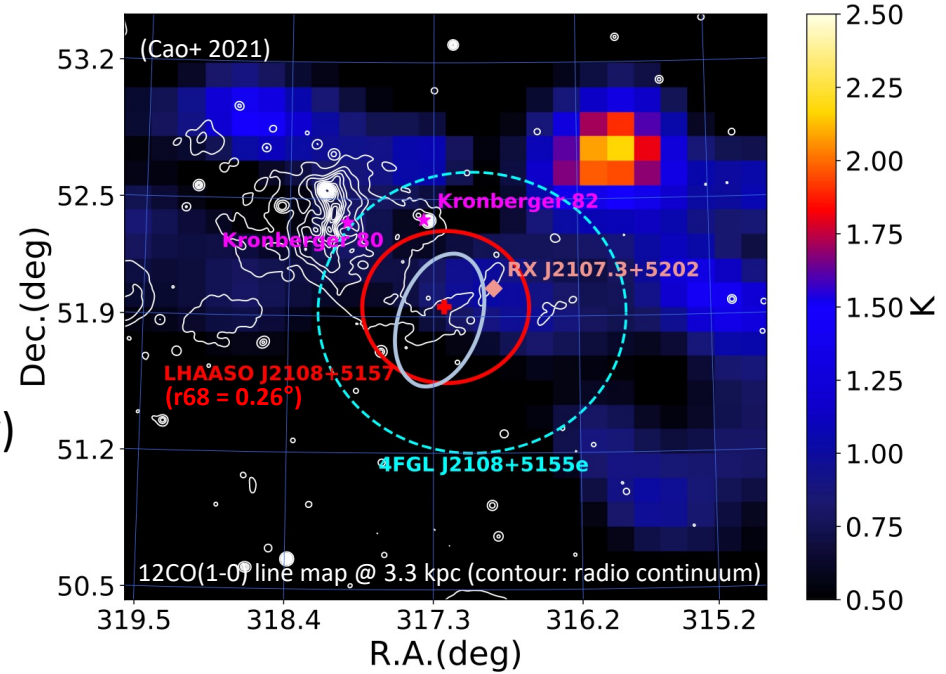
# *VERITAS observed three LHAASO sources: among the first IACT follow-up observations*

- **Very Energetic Radiation Imaging Telescope Array System (VERITAS)** @ Amado, AZ
  - Array of four 12-m imaging air Cherenkov telescopes (3.5° field of view)
  - **Sensitive in 85 GeV to > 30 TeV, PSF 0.08° @ 1 TeV**, 1% Crab in < 25 hrs
- Follow-up observation of three LHAASO sources in 2021-23
  - **LHAASO J2108+5157 ("Dark PeVatron")**: 35 hrs
  - **LHAASO J0341+5258 ("Dark PeVatron")**: 50 hrs
  - **LHAASO J0621+3755 (pulsar halo candidate)**: 40 hrs

# *LHAASO J2108+5157 is a bright UHE source with multiple potential hadronic counterparts.*

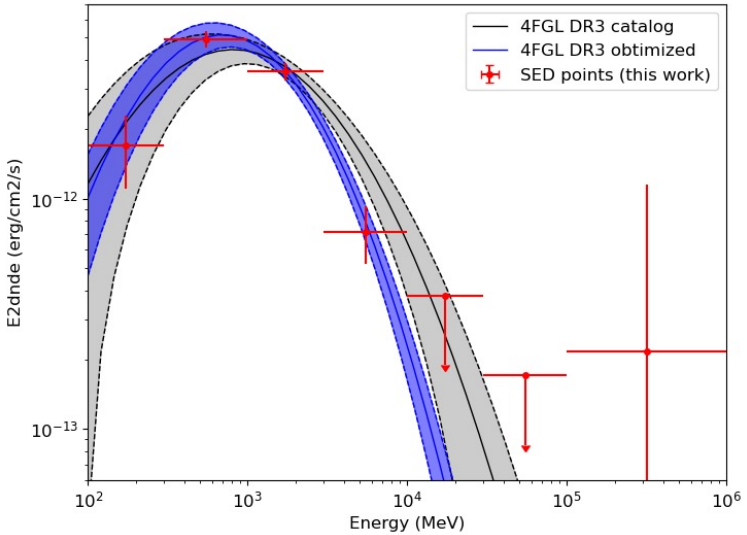
| | 1LHAASO J2108+5153u | | |
|---|---|---|---|
| | **Sig.** | **r68 (°)** | **PL $\Gamma$** |
| **WCDA (1-25 TeV)** | $8\sigma$ | 0.21 | 1.4 |
| **KM2A (> 25 TeV)** | **$15\sigma$ > 100 TeV** | 0.29 | 3.0 |

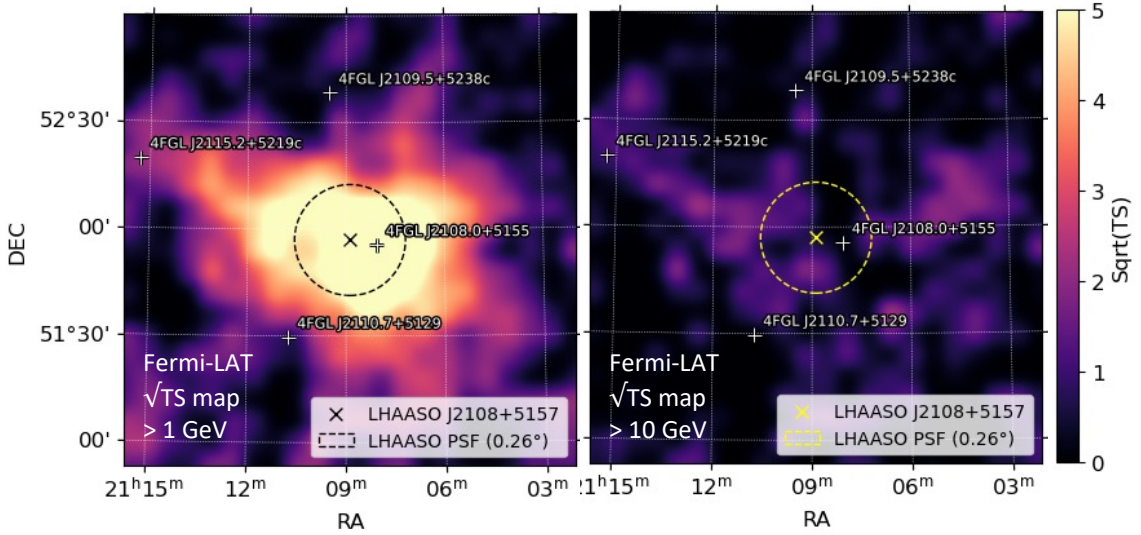
- **Hadronic** PeVatron?
  - **Molecular clouds** @ 1.6, 3.3 kpc
  - **Young star clusters** (0.62°, 0.45° away)



# *Nearby unidentified Fermi-LAT source shows a pulsar-like spectrum, a potential leptonic counterpart.*

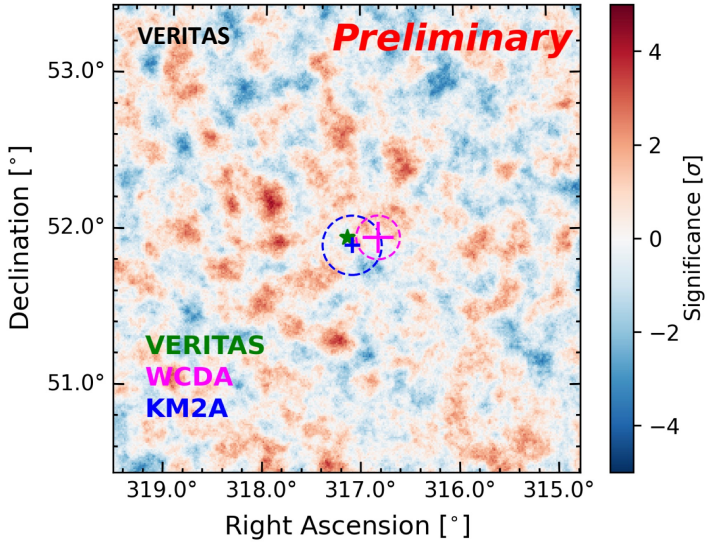
- **Leptonic** PeVatron?
  - Point-like 4FGL J2108.0+5155 (5’ away) sharp cutoff < 10 GeV: **pulsar**?
  - **Our Fermi analysis: no significant extension / no other significant source > 10 GeV**

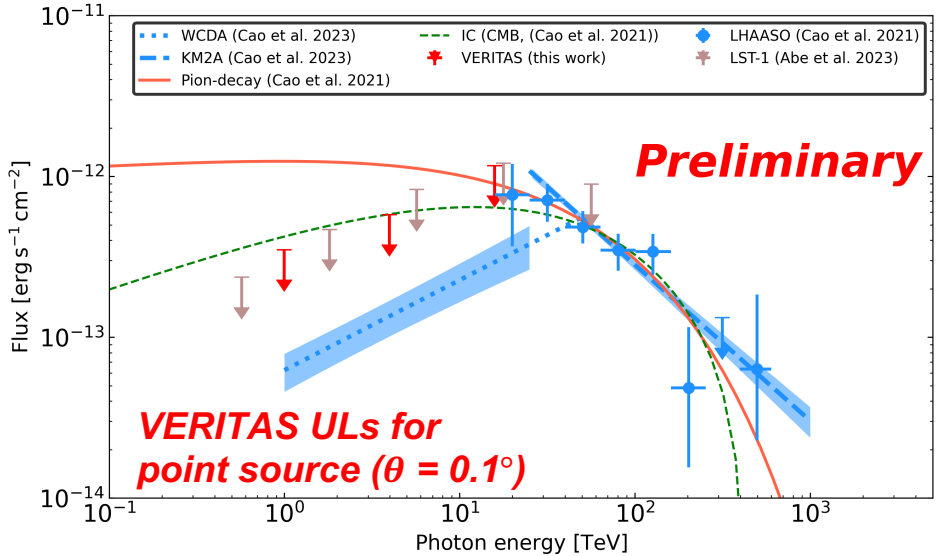


# *LHAASO J2108+5157 was not detected by VERITAS. X-ray emission was not detected by XMM-Newton.*

- **35-hr VERITAS observation yielded non-detection** for both a **point-source ($\theta$ = 0.1°)** and extended-source ($\theta$ = 0.25°) case.
- **123-ks XMM-Newton observation yielded non-detection.**
- Multiwavelength SED modeling is ongoing.

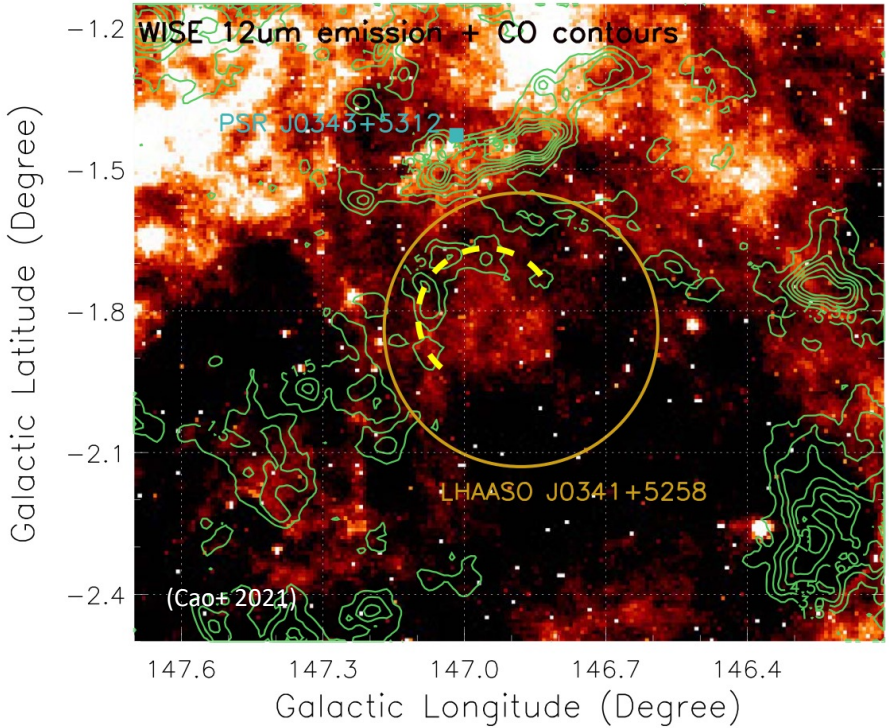


# *LHAASO J0341+5258 is a UHE source without any prominent hadronic / leptonic counterpart.*

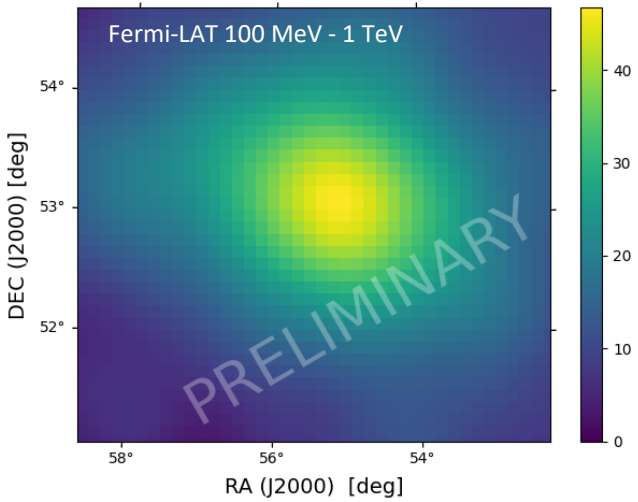
| | 1LHAASO J0343+5254u | | |
|---|---|---|---|
| | **Sig.** | **r68 (°)** | **PL $\Gamma$** |
| **WCDA (1-25 TeV)** | $9\sigma$ | 0.5 | 1.7 |
| **KM2A (> 25 TeV)** | $3\sigma$ > 100 TeV | 0.3 | 3.5 |

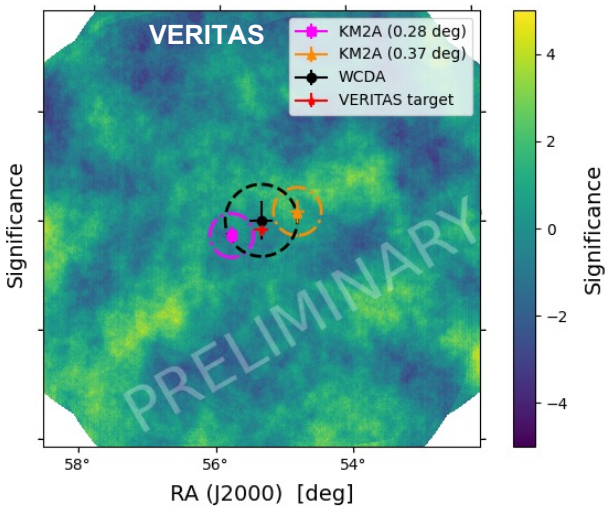
- **1LHAASO J0339+5307**
  - $11\sigma$, point-like, PL $\Gamma$ = 3.6 > 25 TeV
- **No prominent hadronic counterparts**
- **PSR J0343+5312** (radio pulsar) @ 2.5 kpc
  - $\tau$ = 2.28 Myr, $\dot{E}$ = 7.3e31 erg/s
  - **Too weak to power a leptonic PeVatron**

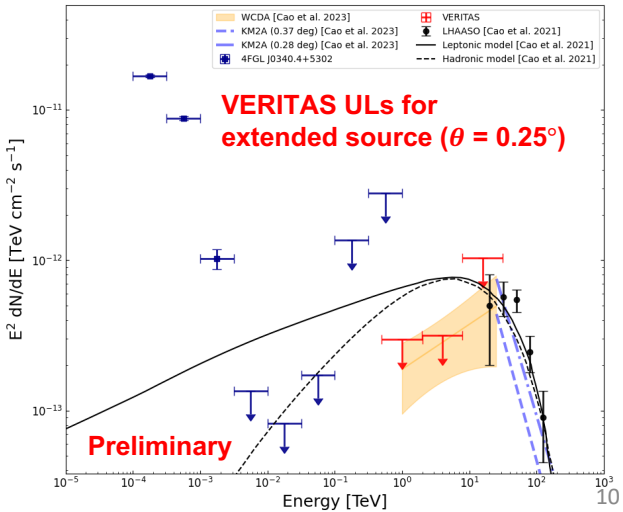


# *LHAASO J0341+5258 was not detected by VERITAS. Nearby Fermi source is bright below 10 GeV.*

- **50-hr VERITAS observation yielded non-detection** for both a point-source ($\theta$ = 0.1°) and **extended-source ($\theta$ = 0.25°)** case.
- Unidentified Fermi source 4FGL J0340.4+5302 (9’ away) sharp cutoff < 10 GeV: pulsar?
- 100-ks XMM-Newton observation has been scheduled. MW SED modeling is ongoing.



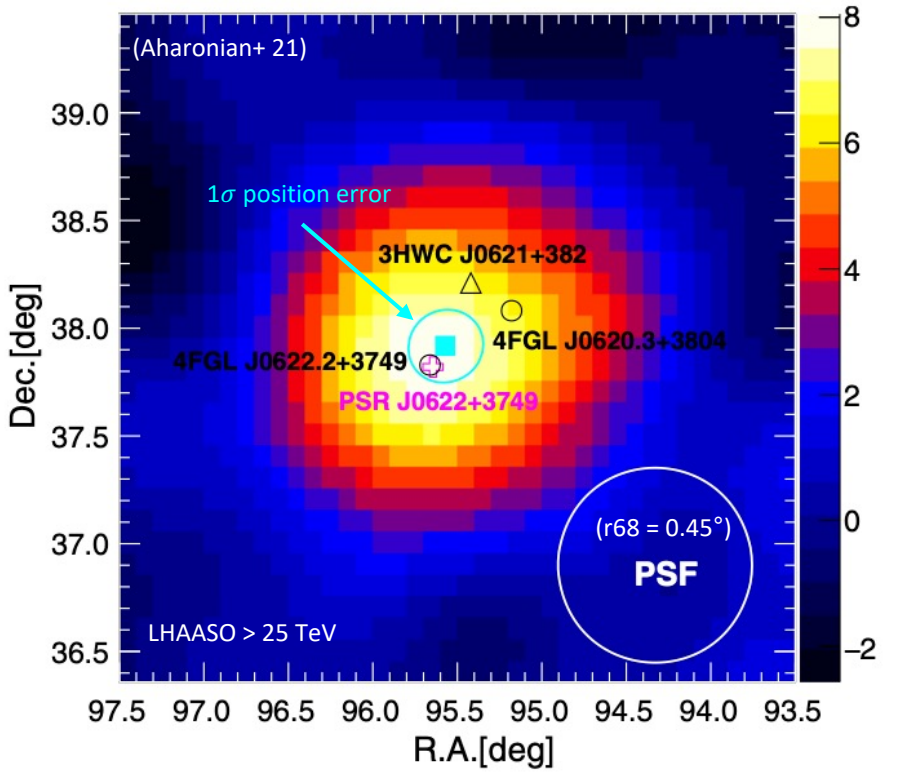



# *LHAASO J0621+3755 is a VHE source around an old gamma-ray pulsar.*

| | 1LHAASO J0622+3754 | | |
|---|---|---|---|
| | **Sig.** | **r68 (°)** | **PL $\Gamma$** |
| **WCDA (1-25 TeV)** | $7\sigma$ | **0.75** | 1.8 |
| **KM2A (> 25 TeV)** | $24\sigma$ > 25 TeV | **0.69** | 3.7 |

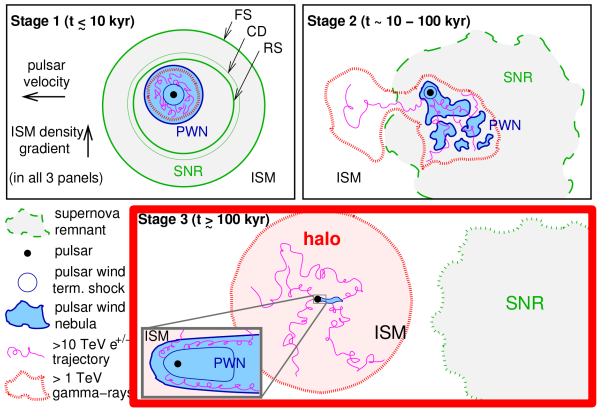
- **PSR J0622+3749** (Fermi pulsar) @ 1.6 kpc
  - **$\tau$ = 207.8 kyr, $\dot{E}$ = 2.7e34 erg/s**
  - 4FGL J0622.2+3749 (7’ away)
  - No PWN in any wavelength



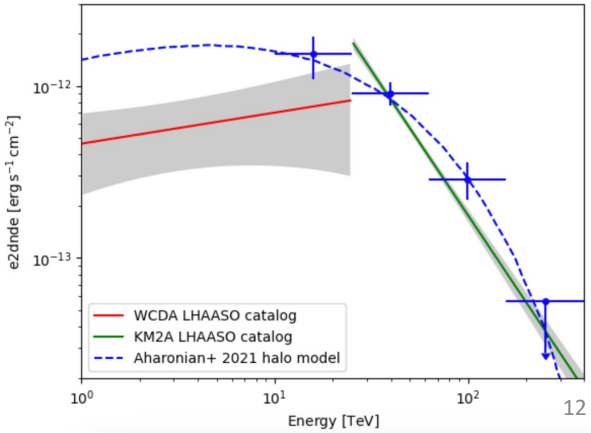
# *For this pulsar halo candidate with large extension, careful background estimation is required.*

- **Pulsar halo?**

| Name | $L_{sd}$ ($10^{34}$ erg s$^{-1}$) | $\tau$ (kyr) | $d$ (kpc) |
|---|---|---|---|
| J0622 + 3749 | 2.7 | 207.8 | 1.60 |
| Geminga | 3.3 | 342.0 | 0.25 |
| Monogem | 3.8 (Aharonian+ 21) | 110.0 | 0.29 |

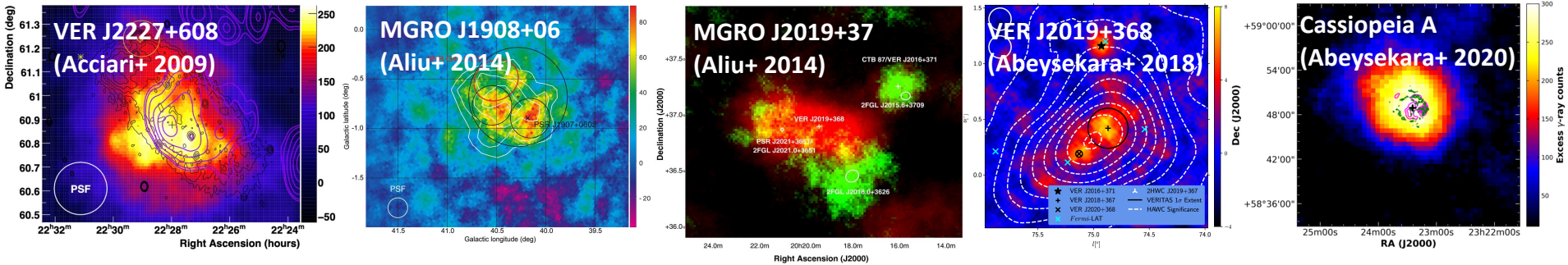



- Analysis of **40-hr VERITAS observation** is ongoing.
- **Challenges in background estimation: r68 = 0.75° vs. VERITAS field of view r = 1.75°**
- 100-ks XMM-Newton observation to be scheduled.



# *VERITAS will continue the Galactic PeVatron search. Synergy with future MW instruments is expected.*

- **The Galactic PeVatron search is one of VERITAS's key science projects.**




- **Synergy with hard X-ray observation**
  - Resolve synchrotron spectrum of the CRs emitting in UHE
  - Detect cutoff due to particle Emax without KN effect
  - Constrain magnetic field → shock acceleration mechanism
  - Provide detailed morphology of CR acceleration sites
  - **Galactic PeVatron search with HEX-P: 9/14 (Thu) 2 PM GWMM**